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14. ABSTRACT
High altitude exposure in aircraft, hypobaric chambers and with extravehicular activity (EVA) in space results in an inherent risk of altitude decompression sickness (DCS). In the past, general guidelines for safer altitude exposure have been developed through costly, time-consuming studies, each specific to unique scenarios of altitude exposure. Rapidly changing technology in aircraft design and mission requirements demand improved capabilities in predicting DCS risk during mission planning and execution. In 1990, a new bubble growth algorithm and a statistical model based on the existing USAF DCS Database were initiated at Brooks AFB. The first version of this combined model was completed in 1996. A model validation study using human subjects was completed in 1999. An updated version of this model based on the validation results has been produced and the software developed. A portable hand-held model is being developed for use in situations requiring more flexible operations (e.g. high altitude parachuting). Application of this technology would specifically aid aviators, special operations personnel, and civilian aviators in determining altitude DCS risk.

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ALTITUDE DECOMPRESSION SICKNESS RISK ASSESSMENT COMPUTER (ADRAC) DEVELOPMENT

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ABSTRACT

High altitude exposure in aircraft, hypobaric chambers and with extravehicular activity (EVA) in space results in an inherent risk of altitude decompression sickness (DCS). In the past, general guidelines for safer altitude exposures have been developed through costly, time-consuming studies, each specific to unique scenarios of altitude exposure. Rapidly changing technology in aircraft design and mission requirements demand improved capabilities in predicting DCS risk during mission planning and execution. In 1990, a new bubble growth algorithm and a statistical model based on the existing USAF DCS Database were initiated at Brooks AFB. The first version of this combined model was completed in 1996. A model validation study using human subjects was completed in 1999. An updated version of the model based on the validation results has been produced and the software developed. A portable hand-held model is being developed for use in situations requiring more flexible operations (e.g. high altitude parachuting). Application of this technology would specifically aid aviators, special operations personnel, and civilian aviators in determining altitude DCS risk.

INTRODUCTION

Decompression sickness (DCS) is caused by exposure to significant reductions in environmental pressure. These situations are encountered during diving, high altitude exposures or artificially induced pressure changes in hyperbaric or hypobaric chambers. For large and rapid pressure reductions, supersaturation occurs as a result of the slow tissue gas exchange processes for expelling excess nitrogen. These gases, which come out of solution when tissues are sufficiently supersaturated, collect as bubbles in the tissue. The size and location of these bubbles are thought to have a significant effect on the resulting DCS symptoms. The risks can be minimized or prevented with sufficient denitrogenation by prebreathing pure oxygen (preoxygenation) before such exposures.

The risk of DCS increases with extended exposure times, very high altitudes, and greater physical activity during the exposure. The assessment of DCS risk for both civilian and military personnel under specified flight protocols is a critical problem that the USAF deals with on a regular basis. To provide answers to these questions, and also to obtain a clearer understanding of the effects of denitrogenation, the High Altitude Protection Function of the Air Force Research Laboratory has developed a model to predict DCS risk using physical and physiological principles.

Most altitude DCS modeling has focused on mathematical models describing bubble growth. Van Liew et al. [1] developed a probabilistic model of altitude DCS. The mechanistic principles used in the model were based on the premise that the risk of DCS is related to the number of bubbles and the

volume of gas that can be liberated from a unit of tissue. Gerth and Vann [2] developed an extensive model for bubble dynamics to provide an assessment of DCS. The bubble dynamic equations were similar to those used by Van Liew et al. Kumar et al. [3], [4], [5], [6] in a series of papers, recognized that survival analysis techniques are the most appropriate to model DCS risk. They developed logistic and loglinear models to predict DCS as a function of Tissue Ratio, which is a measure of tissue nitrogen decompression stress. In a recent paper, Conkin et al [7] discussed in some detail the use of survival times and censoring using the loglogistic model.

The survey of current literature in the area of altitude DCS shows the limitations of the models that are currently in use; e.g. the description of the bubble growth dynamics using approximate (quasi-steady state) models. Such an approach, due to the equilibrium assumption inherent in it, cannot account for the influence of any initial conditions. In the past when approximate models were selected to obtain a non-complicated numerical solution, they frequently yielded erroneous results. Also, most of the current models examine the effect of one or two factors on DCS risk. In reality, the risk of DCS is affected by a number of competing factors; preoxygenation time, exposure time, exercise status, symptom and VGE (Venus Gas Emboli) onset times, and altitude. In order to develop a model that adequately describes the phenomenon of DCS, all these factors should be included in a survival model. Such a model could determine the relative importance of the different factors, and possibly provide a method of controlling the risk of DCS. There is clearly a need for a comprehensive model that includes as many of these factors as possible.

Reports of altitude DCS from the field are rare (8). However, data from chamber studies show varying rates of DCS incidence for simulated operational profiles. With proper procedures (e.g., preoxygenation (Preox), suit/cabin pressurization, etc.), the risk of DCS can be significantly reduced. Countermeasures for preventing DCS are thus not the problem. Rather, the problem facing aircrews is how to quantify the risk of DCS and then select an appropriate combination of available countermeasures compatible with the constraints of a given mission. To quantify the risk of DCS the AFRL has developed an Altitude DCS Risk Assessment Computer (ADRAC), based on a DCS risk prediction model (9,10). A model based on the loglogistic distribution was used to predict the probability/risk of DCS over time as a function of altitude, Preox time, exposure time, exercise, and the time of onset of maximum venous gas emboli (VGE) grade. Before this theoretical model can be transitioned to operational application, it must be validated in the laboratory.

METHODS

There are several methods of DCS risk assessment. The simplest is to find the answer in the literature. However, data on a specific exposure profile is usually not available. The next obvious approach is to conduct an altitude chamber study to determine the DCS risk for that specific profile. However, such studies are expensive and time consuming. People with experience in the field may extrapolate from available data and make a "best guess". The scientifically sound approach is to develop and validate an altitude DCS model that can accurately predict the DCS risk. This model can then become the "chip" in a DCS risk assessment computer, i.e. ADRAC. Potential applications for ADRAC include:

- Mission Planning
- Systems Design
- Real-time Cockpit Display
- Education and Research
- Pressure Suit Control
- Cabin Pressurization Control

Following a lengthy feasibility study, the first version of the ADRAC DCS model was completed at AFRL in 1996. A prospective series of human trials to validate this model were completed in 1999 (11). This model validation was successful and the model was modified to include these new data resulting in greater accuracy. Detailed descriptions of the ADRAC model can be found elsewhere (10). The following is a short outline of the model and its capabilities.

The major components of the ADRAC model include (a) the AFRL Altitude DCS Research Database, (b) statistical models, and (c) a deterministic (bubble growth) model. AFRL at Brooks AFB has conducted experiments on human subjects in a hypobaric chamber for many years, creating a unique database of approximately 2500 altitude exposures with a variety of flight profiles. The subjects were exposed to different altitudes, various preoxygenation times, various exercise levels, and various exposure times. The subjects were monitored continuously and were required to report any pain or other symptoms. If the symptoms were indicative of DCS, the experiment was terminated and the subject repressurized to ground level. During each exposure, venous gas emboli were recorded by precordial 2-D Doppler/echocardiography.

To quantify the risk of DCS, survival models using the loglogistic distribution were developed to predict the probability of DCS incidence and onset time as a function of the following risk factors (9).

- Altitude / Pressure
- Exposure Time
- Preoxygenation Time
- Exercise
- Time to Maximum Bubble Grade (Bubble Growth Model)

The bubble growth model consists of a program that numerically solves a system of equations describing bubble growth due to a hypobaric decompression (10). It returns a single value; the onset time of maximum bubble radius. The model consists of an advection-diffusion equation coupled with two ordinary differential equations; the conservation of mass and momentum equations. The system is in spherical coordinates and it describes the growth of a single bubble surrounded by a limited amount of tissue. Since blood leaving the capillaries removes nitrogen gas from the system, a sink term in the diffusion equation was added to account for loss of tissue nitrogen.

RESULTS

To evaluate these models, validation data were collected at AFRL (11). The profiles in the validation study were selected to fill in gaps in the database where little or no data was available. Five profiles were selected for the validation study (n=30/profile). Data from these exposures were not used in the development of the initial model being validated. The endpoint for each exposure was the onset of DCS symptoms. The actual incidences of DCS (A_{DCS}) and VGE (A_{VGE}) from these exposures were compared to those predicted by the model (P_{DCS}). To assess the goodness of fit of the model, we used the 95% confidence band.

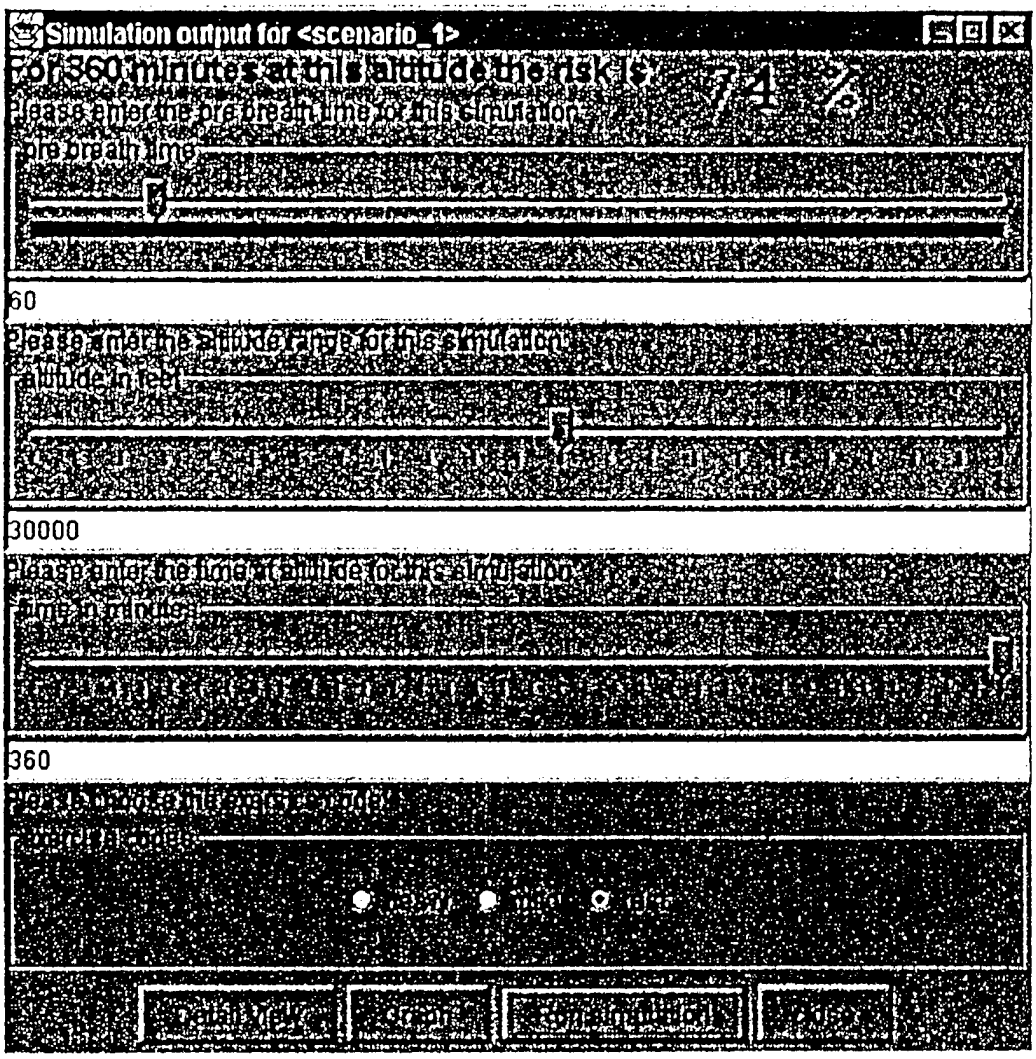
For these 5 profiles, the actual DCS incidence was within the 95% confidence intervals of that predicted by ADRAC model (Table 1).

Results from these and other studies required new stratified models to be developed and adjusted for interactions between pressure and exercise (12). The database used to develop the initial model contained no information on heavy exercise, whereas three of the five validation profiles above used heavy exercise.

Table 1. Results of validation

Profile	Preox (min)	Alt (ft)	Exercise	P_{DCS} (%)	A_{DCS} (%)
1	90	35,000	Mild	93	91
2	30	25,000	Heavy	62	61
3	75	30,000	Rest	52	58
4	0	18,000	Heavy	17	13
5	15	22,500	Heavy	38	30

Table 2. Example ADRAC display



We have been able to adjust the model to account for the heavy exercise, and this has allowed us to better predict the onset of symptoms for shorter exposures at the higher altitudes. Also, at the lower altitudes, very little data on zero preoxygenation was available when the initial model was developed. The validation data and additional low altitude exposure data have allowed us to modify the model to account for these low altitude

predictions. This new version of the model is the basis for the Altitude DCS Risk Assessment Computer (ADRAC) currently under development at AFRL.

SOFTWARE DEVELOPMENT

Following the validation of the model, we developed a software application that uses the described model to predict altitude decompression sickness. The software has been written in Java, so that it can run on any operating system. In the software, the user can create/modify/delete scenarios. A scenario is a set of parameters that the user specifies, consisting of 4 inputs to the model:

- Altitude – The user can specify 18,000 to 40,000 feet
- Exposure Time - From 0 to 360 minutes
- Exercise Level – Either rest, mild, or heavy
- Pre-Breathe Time – From 0 to 480 minutes

The user can also input a name and description for the scenario (a sentence), which are not used in the model. Figure 2 illustrates the menus for specifying a scenario. After creating the scenario(s), the user can then select scenarios of interest and obtain the risk associated with it. The risk is calculated using the model and displayed. A table view shows the detailed risk at the different times, and a graph view plots these values (not shown). While viewing the output, the user can dynamically modify the scenario and, "on the fly", view the subsequent changes to his risk, and the effect on the graph and table is immediately seen. The old values in the graph will not be erased, and the new plot will be superimposed, so the user can quickly see the differences by the changes in his parameters. Scenarios are saved to disk so that the user can maintain information from session to session.

CONCLUSIONS.

The predictive ability and accuracy of the ADRAC model has been validated by a total of 5 profiles using human subjects exposed in an altitude chamber. The data from these profiles has been added to the model database and the model modified to improve its predictive capability. This study represents the first time an altitude DCS model has been successfully validated using rigorous statistical techniques.

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BIOGRAPHIES

Andrew A. Pilmanis is a senior research physiologist and Chief of High Altitude Protection Research at the Air Force Research Laboratory's Biodynamics & Protection Division. He has M.S. and Ph.D. degrees in physiology from the University of Southern California (USC). He is a Fellow of the Aerospace Medical Association and President of the the Life Sciences and Biomedical Engineering Branch (1997-1998) of the Aerospace Medical Association. Previously, he was on the faculty of the USC School of Medicine and director of their Hyperbaric Research and Treatment Facility on Santa Catalina Island. He was Program Director (1980-1985) for the joint NOAA/USC Undersea Research Program, responsible for the design and construction of the laboratory's saturation

Lambros J. Petropoulos is the Decompression Sickness (DCS) Model Development Specialist for Wyle Laboratories, Life Sciences, Systems and Services at the Air Force Research Laboratory, Brooks AFB, TX. His provides scientific and technical support by developing and validating a mathematical computer model that will predict the risk of altitude DCS associated with high altitude, and/or space operations. Mr. Petropoulos has an M.S in Applied Mathematics (Computational Fluid Mechanics) from the State University of New York at Stony Brook. His research interests include analytical and numerical solutions to biological models, diffusion-convection problems (single and multi-component (ADRAC/ARGOX) bubble growth models), and heat transfer problems (time-averaged Navier-Stokes equations).

Nandini Kannan is an Associate Professor in the Division of Mathematics and Statistics at the University of Texas at San Antonio. She has an M.A. degree in Mathematics from the University of Pittsburgh, and a Ph.D. degree in Statistics from the Pennsylvania State University. Dr. Kannan's research interests include Statistical Signal Processing, Environmental Statistics, and Survival Analysis. She has been associated with the Air Force Research Laboratory as Summer Faculty and Research Associate developing survival models for altitude decompression sickness.

Francine Evans is a co-founder of NCrist Software Solutions in Houston, Texas. She earned her Ph.D. in Computer Science in August 1998 from Stony Brook University, where she was an NSF scholar. Her research interests are Computer Graphics, Virtual Reality and Algorithms Design. Specifically, her thesis involved developing a new technique to speed up rendering time in computer graphics. This work was a finalist in the 1997 Long Island Software Awards. Previously, she has worked at Brookhaven National Laboratory, Northrup Grumman, VETL/NASA, and currently is at Schlumberger.

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James T. Webb is a lead scientist for Wyle Laboratories in San Antonio, Texas. He has M.S. and Ph.D. degrees from the University of Washington and is board certified in Aerospace Physiology by the Aerospace Medical Association. Dr. Webb holds an Airline Transport Pilot certificate and obtained over 4300 flying h including 250 combat h in Vietnam (F-4Ds) and 2800 h of C-141A experience prior to his USAF retirement. He is a past-President of the Aerospace Physiology Society (1993-1994) and the Life Sciences and Biomedical Engineering Branch (1995-1996) of the Aerospace Medical Association. Dr. Webb is a Fellow of the Aerospace Medical Association, received its 1999 Leverett Environmental Science Award, and currently investigates decompression sickness risk at Brooks AFB, TX.

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